Image transfer through coherent population trapping based on an atomic ensemble

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We report on an experiment on transferring an image through coherent population trapping (CPT) effect in a hot rubidium vapor. We demonstrate experimentally that an image can be transferred from a control light to a probe light. Moreover, we describe the demonstration that the image can be transferred from a control light to two different probes showing a feasibility of transferring an image onto multiple probes. We believe that this effect definitely has important applications in image metrology, high dimensional information transfer in quantum information field, etc.

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1. Introduction

The ability to optically control an image is very important for biology imaging,[1] medical imaging,[2] etc. Modern optical techniques allow us to arbitrarily manipulate light carried images by using atoms based on electromagnetically induced transparency (EIT) or coherent population trapping (CPT).[3,4] These effects have been widely used in the scope of light-matter interactions, such as the preparing of entangled photon pairs,[5–11] slowing and stopping of a light pulse,[12–14] and very recently, the manipulating of an optical image,[15–17] the storing and retrieving of image.[18–23] Constructing a technique of spatial multiplex imaging based on interaction between light and matter holds a promise in multiple images quantum information processing. Here, we report on an experiment on image transfer based on CPT effect. Because the property of medium is spatially modulated and dependent on the structure of the control field, an image imprinted in a strong control beam is transferred into a weak probe field. Furthermore, we demonstrate experimentally that the image can be transferred from a control light to two different probe fields, thus showing the ability to transfer multiple images. We believe that this effect definitely has potential applications in image metrology, high-dimensional information transfer in quantum information field, etc.

2. Experiment and results

All experiments were performed within the D2 transition of ^{85}Rb. With a control and a probe beams used in the experiment, the atoms are accurately modeled as a three-level atom interacting with two lasers. The energy levels diagram is shown in Fig. 1(a). The Zeeman sublevels of the ground state $5S_{1/2}$ $(F=3)$ and the excited state $5P_{3/2}$ $(F=4)$ form a three-level lambda system. $|1\rangle$ and $|3\rangle$ refer to the ground state and the stable state respectively, $|2\rangle$ denotes the excited state. A weak probe light with Rabi frequency of Ω_2 and a strong control light with Rabi frequency of Ω_1 act on the transitions from $|2\rangle$ to $|3\rangle$ and from $|1\rangle$ to $|3\rangle$ respectively. Δ_c and Δ_p are the detuning of the control light and the probe light from their respective transitions respectively. Before trying to perform the experiment, we first check whether the image transfer is workable theoretically. The density matrix equation of motion is

$$\frac{\mathrm{d}\rho}{\mathrm{d}t} = -\frac{\mathrm{i}}{\hbar}[H,\rho] - \Gamma_{ij}\rho_{ij}. \tag{1}$$

Here, H is the effective interaction Hamiltonian, Γ_{ij} $(i \neq j)$ is the complex decay rate from $|i\rangle$ to $|j\rangle$ and Γ_{ij} $(i=j)$ is the decay rate of ρ_{ii}. Under the condition of strong control and weak probe beams, the calculated imaginative part of the element of the density matrix $\mathrm{Im}(\rho_{23})$ is related to the transmission of the probe. During the derivation of the above equation, we let $\Omega_1^2+\Omega_2^2=\omega^2$, $\Delta_p-\Delta_c=\delta$, $\gamma_{21}=\gamma_{23}$, and $\rho_{33}=1/2$, with γ_{21} and γ_{23} being the relaxation rates at the respective transitions.

In our experiment, a homemade binary mask written digit "7" is inserted in the control beam, the "7" is transparent, and the other part of the mask is opaque, therefore our numerical calculation takes the image of the digit "7" imprinted in the control beam as an input image, i.e., the control light has the shape of "7" as shown in Fig. 1(b). The Rabi frequency of control field is modulated as the structure of "7" by a step function. Taking the parameters as follows: $\Delta_p-\Delta_c=\delta=0$, $\Omega_2=2$ MHz, $\gamma_{21}=\gamma_{23}=6$ MHz, $\gamma_{31}=3$ MHz, $\Omega_1=200$ MHz, the transmitted probe profile through the Rb cell, calculated by using Eq. (1), is shown in Fig. 1(c). It is very clear that there is almost the same image imprinted in the probe beam

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as the image imprinted in the control beam. The transmission property of the medium is structured by the control field due to the atomic coherence of atoms, which makes the transparency of the probes dependent on the structure of the control field. So the image in the control beam can be transferred into the probe beam in principle. Here, we omit the Doppler effect for simplicity of calculation. The more detailed calculations about the image transfer can be found in Ref. [24], in which the dynamic propagation behavior of image is investigated via Maxwell's equations.

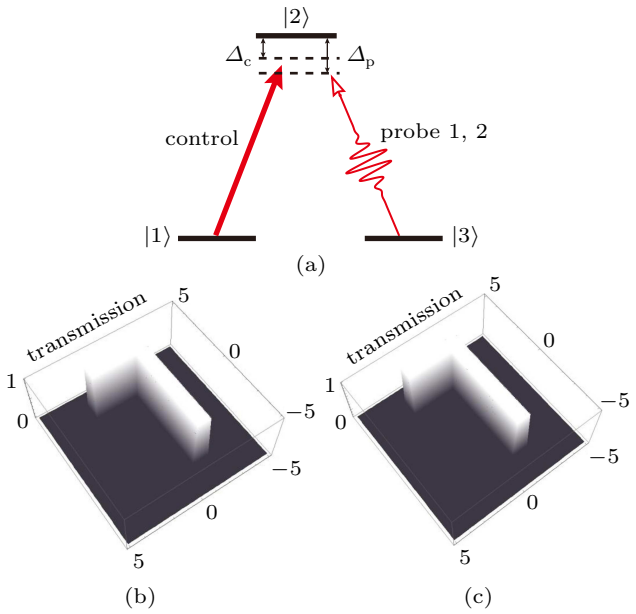


Fig. 1. (color online) (a) Energy diagram of the ^{85}Rb atom. (b) The image of the mask imprinted in the control beam (b) and the transferred image in the probe beam (c) calculated from Eq. (1).

Next, we consider how to realize an image transfer in the experiment. The experimental setup is depicted in Fig. 2. A laser at 780-nm wavelength, from an external cavity diode laser (DL100, Toptica) stabilized to the $5S_{1/2}\,(F=3) \rightarrow 5P_{3/2}\,(F=4)$ transition of ^{85}Rb atom, is divided into two beams with perpendicular linear polarizations, i.e., the control beam and the probe beam, by using a 1/2 waveplate and a polarization beamsplitter. The control beam passes through a homemade mask written digit "7", and the "7" is transparent as mentioned above and the other part of the mask is opaque. Therefore the control beam has a shape of the mask. Several lenses (L1–L5) with different focus lengths are used to make the image propagate parallelly through an Rb cell to reduce the diffraction. The control beam has a waist of 6 mm and can cover the mask. The probe beam has a waist of 4 mm. Similarly, two lenses (L6 and L7) with different focus lengths are used to make the probe propagate parallelly through the Rb cell too. The control and probe beams are arranged to counter-propagate through the Rb cell in order to reduce the noise. Two 1/4 λ waveplates before the cell convert the control and probe polarizations into the left and right circularly polarized beams respectively, and these circularly polarized beams are converted into linear polarizations again after the cell. The probe beam is separated from the control beam by using a polarization beamsplitter and its spatial intensity distribution is monitored by an imaging system, which consists of the lens L8 and a CCD camera (a commercial product which is usually used to monitor atom fluorescence). The Rb cell is 5-cm long, which contains pure ^{85}Rb and is placed within a three-layered magnetic shield.

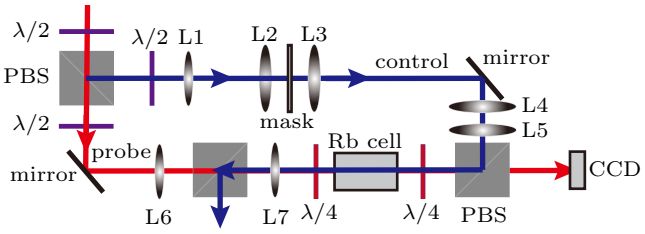


Fig. 2. (color online) Experimental set-up for the image transfer from control field to probe field. The solid line represents the path of the probe beam and the blue line denotes the path of the control beam. PBS: polarization beamsplitter, $\lambda/2$: half waveplate, L1–L7: lenses, and $\lambda/4$: quarter waveplate.

In the experiment, when we monitor the CCD, we find that the image of the mask appears in the probe beam, which means that the image of the mask imprinted in the control beam is transferred to the probe beam. Figure 3 shows an image obtained by CCD in the probe beam under the condition of the control power of 3.85 mW, probe power of 300 μW, and the temperature of the Rb cell of 58 °C. If we block the control, the probe beam is absorbed completely, and nothing can be obtained by CCD. So figure 3 clearly shows that the image of the mask can be transferred from the control beam to the probe beam.

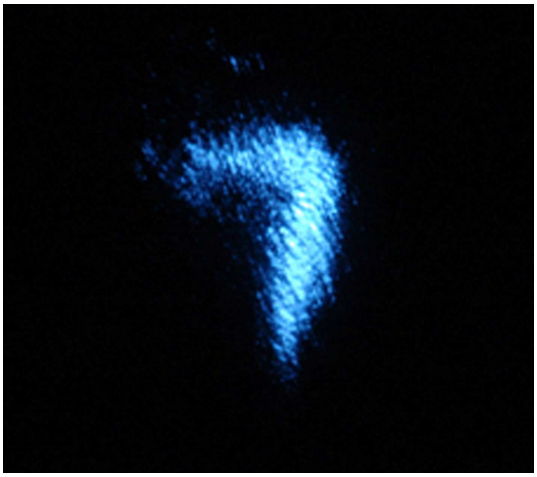


Fig. 3. (color online) Transferred image from the control beam to the probe beam under the condition of control power 3.85 mW, probe power 300 μW, cell temperature 58 °C.

The image shown above is clear, but is smoothed, and the sharp edges of the image are softened. A main reason is the diffractive effect of light during the propagation. Any image imprinted on the probe beam and propagating in the free space will undergo a paraxial diffraction spreading and eventually blurs. In addition to the regular free space diffraction, the

probe beam with image is slowed because CPT effect undergoes diffusion due to the atomic motion in the Rb cell, which makes the image further distorted.

Next, we consider the experiment in which there are two different probe beams. In this experiment, the mask is still in control beam. In contrast to the scenario in the above experiment, the probe beam is divided into two beams by a beam-splitter: probe 1 and probe 2. Both beams with an identical waist of 4 mm pass through the cell with a small angle. The angle between two probe beams is 2θ, and the angle between the control beam and the probe beam is θ, and $\theta \approx 1^{\circ}$. We use a CCD to monitor separated probe beams 1 and 2. If the control beam is off, both probe beams are completely absorbed by Rb cell. When the control beam is on, we find that there is one image in each probe beam. The experimental results are clearly shown in Fig. 4. There is small difference between the images in probe beams 1 and 2, and this difference may originate from the different optical systems in the probe beams 1 and 2. We believe that this result can be extended to the case in which more probe beams are used, i.e., the image of the mask in the control beam can be transferred to many probe beams. We believe that this result can be found to have very important applications such as in image metrology, etc. The images obtained in this case are a little different from the image shown in Fig. 3: the image in Fig. 4 looks bold. The possible reason is the diffusion effect of the atom. Because there is an angle between the control beam and the probe beam, the overlap between them becomes small compared with that in the counter-propagation case, the diffusion effect has large influence in non-collinear case. Another possible reason is the diffractive effect of the probes.

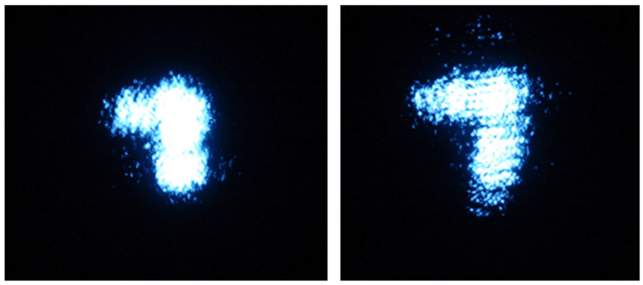


Fig. 4. (color online) Transferred image in probe beam 1 (left) and in probe beam 2 (right). The cell temperature is about 57 °C, the control beam power is about 3.75 mW, and the each probe beam power is 100 μW.

3. Conclusions

In this work, we report an experiment of all optically transferring an image based on atomic CPT effect. We find that the image can be transferred from a control light to a probe light. Further, we realize the image transferring from a control light to two probes, giving an ability to transfer an image onto multiple probe beams. Such experimental results clearly show some interesting properties of CPT, and we believe that this effect definitely has important applications in image metrology, quantum information, etc.

References

[1] Bruce E Cohen 2010 *Nature* **467** 407
[2] Eric Lantz 2008 *Nat. Photon.* **2** 71
[3] Harris S E 1997 *Phys. Today* **50** 36
[4] M Kiffner, J Evers and M S Zubairy 2008 *Phys. Rev. Lett.* **100** 073602
[5] Duan L M, Lukin, M D, Cirac J I and Zoller P 2001 *Nature* **414** 413
[6] Kuzmich A, Bowen W P, Booze A D, Boca A, Chou C W, Duan L M and Kimble H J 2003 *Nature* **423** 731
[7] Balic V, Braje D A, Kolchin P, Yin G Y and Harris S E 2005 *Phys. Rev. Lett.* **94** 183601
[8] Matsukevich D N and Kuzmich A 2004 *Science* **306** 663
[9] Du S W, Kolchin P, Bethangady C, Yin G Y and Harris S E 2008 *Phys. Rev. Lett.* **100** 183603
[10] Chen Q F, Shi B S, Zhang Y S, Feng M and Guo G C 2008 *Opt. Express* **16** 21708
[11] Lu X S, Chen Q F, Shi B S and Guo G C 2009 *Chin. Phys. Lett.* **26** 064204
[12] Hau L V, Harris S E, Dutton Z and Behroozi C H 1999 *Nature* **397** 594
[13] Kash M M, Sautenkov V A, Zibrov A S, Hollberg L, Weich G R, Lukin M K, Rostovtsev Y, Fry E S and Scully M O 1999 *Phys. Rev. Lett.* **82** 5229
[14] Liu C, Dutton Z, Behroozi C H and Hau L V 2001 *Nature* **409** 490
[15] Ding D S, Zhou Z Y, Shi B S, Zou X B and Guo G C 2012 *Opt. Commun.* **285** 1954
[16] Ding D S, Zhou Z Y and Shi B S 2014 *Opt. Lett.* **39** 240
[17] Yang L R, Wang C F and Wang F 2015 *Chin. Phys. Lett.* **32** 94203
[18] Shuker M, Firstenberg O, Pugatch R, Ron A and Davidsion N 2008 *Phys. Rev. Lett.* **100** 223601
[19] Vudyasetu P K, Camacho R M and Howell J C 2008 *Phys. Rev. Lett.* **100** 123903
[20] Ding D S, Wu J H, Zhou Z Y, Liu Y, Shi B S, Zou X B and Guo G C 2013 *Phys. Rev. A* **87** 013835
[21] Ding D S, Wu J H, Zhou Z Y, Liu Y, Shi B S, Zou X B and Guo G C 2013 *Phys. Rev. A* **87** 053830
[22] Ding D S, Zhou Z Y, Liu Y, Shi B S and Guo G C 2013 *Nat. Commun.* **4** 2527
[23] Ding D S, Zhang W, Zhou Z Y, Shi S, Wang X S, Jiang Y K, Shi B S and Guo G C 2015 *Phys. Rev. Lett.* **114** 050502
[24] Li H b, Sautenkov V A, Kash M M, Sokolov A V, Welch G R, Rostovtsev Y V, Zubairy M S and Scully M O 2008 *Phys. Rev. A* **78** 013803